Agent-based evacuation model of large public buildings under fire conditions

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ABSTRACT

It is an important issue that all occupants should be able to evacuate to safety from large public buildings under fire conditions. In this paper, a system simulation model is presented, in which a physical model and a mathematical model are included. Based on the agent technology, a computer program is developed to simulate and analyze the egress progress in large public buildings through combining rule reasoning with numerical calculation, and some crowd pedestrian flow phenomenon, such as aching, rerouting, etc., could be observed from visual illustration of the scenarios. By coupling with the fire scenario simulated by CFD technology, the computer simulation program may represent the overall and dynamic process of occupants’ evacuation under fire expansion, and the mutual relationship between occupants’ safety and fire hazard. An indoor stadium which was used as a competition venue for 2008 Beijing Olympic Games is studied as a case.

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With development of the society, many large public buildings, such as libraries, gymnasiums, stations, exhibition halls and airports, have been built in China. Once fire occurs in these buildings, fire and fumes will spread rapidly which will result in a difficult evacuation and cause serious injury to human. Since the costs of holding practical experiments cannot be easily afforded and the experimental data are difficult to capture, the evacuation simulation by computer has become popular in recent years.

It is not easy to predict evacuation performances for large public building with complex layouts. The situation will become even more sophisticated when considering the interaction between occupants and fire/fumes. Some evacuation models, such as EGRESS, EXODUS, SIMULEX, EXIT, WAYOUT [1], have been successfully established based on fine or coarse networks. These models can be used to simulate occupant evacuation and evaluate the evacuation efficiency for buildings. On the other hand, for fire simulation, some models have been applied to calculate heat and mass transfer data in fire field. These models include: CFAST, CONTAM, FIRAC, MELCOR, etc. [2]. The development of fire simulation models makes it possible to find out relevant quantity distribution in field without practical experiments. But the evacuation model and fire simulation model must be properly integrated in order to produce accurate simulation for occupants in fire. As the combination of these two isolated simulation models, the module representing the interaction between occupants and fire field is crucially important for the integration.

In this paper, a basic Agent-based evacuation model is constructed firstly. The intelligent technology is induced in this model to represent self-motivation, response and decision-making ability of human in the escape progress. Then, an effective approach which can be adopted to simulate occupant evacuation in fire environment is presented. On the basis of the integration of evacuation simulation model and fire simulation model, a simulation model for occupant evacuation in fire environment, AIEva is proposed.

1. Basic Model of Evacuation

Based on the physics modeling principle, the evacuation progress is abstracted as a progress that the agent objects are driven by various factors with time flow. Characters and behaviors of individual are simulated by a mathematics model and some rules. An agent-based evacuation simulation program, AIEva, is then developed based on the physical systems dynamical model. The model includes two sub-models, spatial environment model (SEM) and agent decision model (ADM).

The macro spatial environment model (SEM) represents building environment in fire at each time step, which includes building layout information and fire field information. Spatially, the building layout is divided into uniform grids. Each grid is occupied by either wall or other obstacle, or human, or otherwise free. It is discovered from many fire hazard cases, that fumes caused by fire is the main factor that threatens human life [3]. Thus, fire and combustion products must be taken into account when the building is on fire. The products may contain toxic substances and bring physical and psychological hazards to the occupants in environment. For instance, in the fire accident that happened in Luo Yang Dong Du department store, approximately 309 people died from fumes poisoning and suffocation. Thus the spread and distribution of fumes has an important affection to crowd evacuation. Meanwhile, occupants will make their response to the
environment and adjust their evacuation strategies according to the surrounding situations. Obviously, in the fire environment an interaction between occupants and fire field exists. Therefore, the task of simulation model is not only to create and append these components but also to accurately represent the relationships among them.

AIEva utilizes FDS (Fire Dynamics Simulator) model to achieve calculation data with respect to fire field at each time instant, i.e. fumes heights et al. Data is saved into fire information database of AIEva system. During the simulation, the data of fire field is read at each time step. Thus each grid in the spatial environment model (SEM) has a fire parameter at each time step. The parameter will affect individual decision and action as a factor during evacuation.

The model assumes each person occupies a 0.4 m×0.4 m space, which is the typical size of each person’s space [4]. So SEM discretizes the building by 0.4 m×0.4 m grid size. Meanwhile the evacuation model generates all the occupants in the environment and produces the simulation for each occupant at each time step. The evacuation behaviors and characters of each occupant under fire conditions should be solved by the ADM. In the model, present status, relative properties and behavior rules are specified for all occupants.

The agent decision model (ADM) was constructed through the integration of intelligent simulation methods including agent technology and rule reasoning etc. As a representation of the occupants, the agents make decisions on behavior at each time instant according to certain rules. They search for corresponding rules with the change of environment so as to adjust themselves.

Each occupant could feel the state only within certain visual field. The model introduces the conception of neighborhood to simulate the effect of local visual field. Around each agent, there exists a neighborhood, which could simulate the occupant’s view field in some cases. The current state parameters of the grid within the neighborhood will affect the agent’s decision at the next step. In the model, we select Von Neumann neighborhood [5] (as shown in Fig. 1) as the neighborhood of each individual. The current behavior of each individual is totally decided by the environmental parameters within the neighborhood. It is reasonable that the movement of people in the building is normally based on the local environment rather than the whole building and fire environment. People usually have not the ability to get detailed knowledge of the whole fire field space. Many old models developed formerly built a schedule escape route by using overall network or equidistant map. These models actually are not taking into account. Thus a basic evacuation model is constructed based on the universality principle, some especial properties will be not taken into account.

At each time step, each agent has three fundamental problems to decide:

(1) The selection of routine, which means where to go at the next step.

This relates to some factors like the building environment (exit position, obstacle distribution etc), fire condition (fire source, fumes condition around etc) and the human psychology. The model represents the effects of these factors on evacuation by ‘environment driving factor’. The ‘environment driving factor’ includes exits driving factor, danger eject factor and crowd attraction factor. Exits driving factor is the function of the distance between targeted exit and every grid within ‘neighborhood’. The grid closest to the exit has the most driving power. This factor will drive individual occupant to move towards exit. Danger eject factor is set to indicate that occupants always tend to keep away from dangerous areas of fire. The closer the grid to the fire source, the greater the eject force. Crowd attraction factor is to denote the trend that most occupants try to follow the crowd nearby during evacuation in most cases. The ‘environment driving factor’ is the weighted linear combination of the above factors with certain probability. The consistence and algorithm of the ‘environment driving factor’ will be introduced in detail in the mathematical model below.

(2) How to decide the variation of speed?

Speed describes how fast the occupant can move within the scene. Normally free walking speed can be regarded between 1.2 m/s and 1.8 m/s. Also some experimental data suggests it varies as a function of age for males and females taken from Ando et al. [1988][6].

Fig. 1. Von Neumann neighborhood (r=2).

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Free walking speed is not available when occupants are restricted by structural characteristics (such as at staircases, corridors, etc.) or flow density. It is obvious that occupants move slowly when the density gets high. Based on the analysis of experimental data, Nelson and MacLennan (1996) proposed the following model to represent the relationship between move speed and flow density [7]. Actually, other factors should be taken into account since it reflects the physical and environmental situation for occupants and influences the move speed as well. The speed of occupant will vary during evacuation due to the effect of some factors, i.e. fumes density, psychology etc. The variable “adjust speed” which summarizes all the factors above is defined.

(3) How to solve the conflict when one occupant contests with others for one grid synchronously?

It is likely that there is more than one occupant entry into one grid \((x_i, y_i)\) at the same time step during the simulation. As we divide the grid to contain only one person, the case that more than one occupant occupy one grid is not allowed. When such instance occurs, the conflict treatment will be performed according to the principle of equal probability. An occupant will be selected in random to enter into the position. Besides, due to the variation of individual speed, when the velocity of the latter person is faster than the former, he either stops to wait in his place or move by side to the front position. At each time step, all agents update the current status simultaneously according to the environment around and self-characters.

According to the former analysis, the whole physical simulation procedure of evacuation is described as follows:

(1) Initialization. User needs to input the position of fire source, building exits and crowd density etc., and divide the grids. The initial location and properties of all agents will be specified before fire occurs.

(2) AIEva reads the fumes parameters of all grids at each time step from database, and all the agents will be visited. Every agent will first observe the state of the grids within the neighborhood as Fig. 1, and then exclude those grids occupied by obstacles or other agents.

(3) The environment driving factor of grids within the neighborhood will be calculated at each time step, which will determine the agent’s movement and direction. The numerical calculation and rule reasoning module will be called according to some parameters, such as the crowd density D, the psychology factor and the smoke status within certain range \((2x \times 2y)\), and then the movement speed could be solved. Through the probability judgment, one most suitable grid will be selected from the neighborhood to become the goal grid at the next step.

(4) Based on the model assumption, one grid could be occupied by at most one person at each time step. Thus if there exists multi-occupants competing for the same grid, i.e. the conflict happens, only one person could enter the grid according to the comparison of velocity, and the other person will either stay at the original grid or move by the side to try the overpass. The action taken is determined by random probability.

(5) Random slowdown. Some agents will be required to slow down and stop moving with certain given probability. It is designed to simulate some accidents in practice, such as loss of the ability to move due to out of strength or panic etc.

(6) All agents are driven to move the accurate place based on the result above, and judged whether they have achieved at the exit or not. If not, the new position of every agent will be decided again through repeating the procedure (2)-(6) with new factors.

(7) Finally, AIEva will estimate whether all occupants have moved to the safe place. If yes, then stopping iteration, all results and parameters for decision will be exported and visualized after simulation.

2. The Mathematics Model

Usually, three different interactions are considered during evacuation: interactions among occupants, interaction between occupant and building and interaction between occupants and fire field. These interactions will affect decision-making and behaviors of occupant. Where, interaction between occupants and fire field is shown in three aspects: psychology effect, reaction to emergency with self experience and personality; social effect, reaction based on social relationship between people; physiological effect, physiological reaction to environment around.

AIEva system was constructed based on the achievements of the former researchers, considering the general properties and main affect factors of evacuation. According to the process of evacuation, the overall simulation process was abstracted as a model space S. The model space contained a grid matrix M, a parameter vector P(t) and the agents aggregate A(t).

It was formulated in the following mathematical model:

\[ S = \{A(t), P(t), M\} \]  

The building layout was divided into uniform grids and represented mathematically by a two dimensional matrix M with coordinates information \((i,j)\) and attribute parameters (such as fumes and temperature parameters). The equation is shown as below:

\[ M = \{(i,j), \text{data} | x_{\min} \leq i \leq x_{\max}, y_{\min} \leq j \leq y_{\max}\} \]

The model represents behaviors by using the agents aggregate \(A = (a_1, a_2, \ldots, a_n)\). The location of the agent could be determined by the grid coordinates. Vector \(L = (l_1, l_2, \ldots, l_n)\) describes the location information of all agents in the building at any time \(t\). Another state variable is the velocity vector of agents \(V = (v_1, v_2, \ldots, v_n)\). At random time \(t\), the state of \(i^{th}\) agent could be expressed with the following formula:

\[ a_i = (l_i, v_i, \theta_i, e_i, p_i) \]

where, \(l_i\) is the location at time \(t, v_i\) is the velocity, \(\theta_i\) is the direction, \(e_i\) is the environment driving factor, \(p_i\) is the psychological effect factor.

No matter how complicated behaviors and psychology are, all factors will finally be represented by the action of agent, i.e. walking speed and routine. Hence, the walking simulation of every occupant is actually the process that the occupant’s velocity and movement direction at each time step and the location to arrive at the next time step are decided by various impact factors.

In fact, the whole simulation process is the iteration process of location vector \(L\) shown as follows:

\[ L_{t+1} = f(L_t, u_t, \theta_t) \]

Before fire, occupant \(i\) always occupies a position \(l_i = (x_i, y_i)\) in the space. After fire occurs, most occupants tend to run to the exit as quickly as possible during evacuation. And they tend to be away from the place where there are fire and fumes. The grid located in ‘neighborhood’ is the possible location for agents to arrive at the next step. In order to simulate the behavior that the agent chooses the reasonable grid to enter in the computer, the conception of ‘environment driving factor’ \(e\), is introduced to represent the effect

![Table 1](image)

<table>
<thead>
<tr>
<th>Degree of familiarity with inside building</th>
<th>Smoke density (extinction coefficient)</th>
<th>Visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfamiliar</td>
<td>0.15 m⁻¹</td>
<td>13 m</td>
</tr>
<tr>
<td>Familiar</td>
<td>0.5 m⁻¹</td>
<td>4 m</td>
</tr>
</tbody>
</table>
of various environmental factors on evacuation, i.e., building layout and fire process. It is a function of various impact factors.

$$e_i = f(s_i, p_i, d_i)$$  \hspace{1cm} (5)

$e_i$ represents the integrated action of various environmental factors within a certain grid $l=(x,y)$, and could be suggested as the following formula expressed as a weighted linear combination equation:

$$e_i = k_s s_i + k_p p_i + k_d d_i$$  \hspace{1cm} (6)

where, $s_i$ is the 'exit driving factor' for the grid $l$, which is the function of distance between grid location $(x_i,y_i)$ and targeted exit. $p_i$ is called as 'danger ejecting factor', which is the function of distance between grid location $(x_i,y_i)$ and dangerous source (such as fire source). $d_i$ means that the closer the grid to the fire source, the more dangerous. So, people will tend to keep away from the dangerous places. When $p_i = 0$, it means agent's 'neighborhood' has no information on location of dangerous source. Then it will not be influenced by this factor. For example, when fire occurs in a room, people may not know the fire condition in other rooms. Instead they take action according to alarm or other information. Moreover, $p_i$ could also be used to calculate the ejecting power of other feature things, such as obstacles etc. Thus the movement that people avoid the obstacle could be simulated.

$d_i$ is the 'crowd attraction factor', which describes and simulates people's behavior of following others. The model selects human density $D$ in certain range $(\Delta x \times \Delta y)$ as the calculation parameter of $d_i$. $k_s$, $k_p$, $k_d$ are weights of the factors, which represent influence degree of every factor.

After the escape direction is selected, each agent has to determine the walking speed toward the next position. The extent of walking speed depends upon the age, gender, profession, health etc. Currently, it is considerably difficult that all these influence factors could be considered in a model. Only those main factors, rather than all factors, are considered in the AIEva model. During evacuation of public buildings, crowd density is usually the most important factor. Many researchers believe that the walking speed of individual occupant relates to crowd density. Nelson etc analyzed experimental data and suggested that an occupant would move freely when population density is less than 0.54 person/m$^2$, and hard to move while population density is beyond 3.8 person/m$^2$. Hence, a basic velocity could be expressed as the function of crowd density within a certain space area $(\Delta x \times \Delta y)$ shown as follows:

$$u_b = f(D_0)$$  \hspace{1cm} (7)

where, $D_0$ is the density in person/m$^2$.

Thompson and Marchant [8] calculated the speed reduction due to proximity of others with the help of speed density curve

![Frame plan of AIEva System.](image)
presented by Ando et al. [9]. If \( d_p \) is the inter person distance (m), then
\[
d_p = \sqrt{\frac{1}{D_0}}
\]  

(8)

The basic velocity \( u_b \) could be calculated by Thompson equation:
\[
u_b = \frac{D_0 - 0.25}{0.87}
\]

(9)

where, \( u_b \) is the average free flow walking speed (1.2 m/s). The speed is unimpeded.

Actually, besides crowd density, other factors, such as psychology, individual character etc, should also be taken into account since they reflect physical and environmental situation of occupants and influence the move speed as well. The variable “adjust_speed” \( u_k \) which summarizes all the critical factors is defined as follows [10]:
\[u_k = \lambda \times u_b
\]

(10)

where, \( \lambda \) is the adjust coefficient.

Many researchers have done much work on this problem. So far there is no appropriate theory to fully describe these factors in quantity. In the AIEva model, the psychology influence on walking speed is considered by a suggested psychology influence factor \( \beta \). The “adjust_speed” \( u_k \) could be the correction of basic velocity \( u_b \) by psychology influence factor \( \beta \).
\[u_k = \beta \times u_b
\]

(11)

It is quite a complex problem to determine the psychology influence. One key factor is the panic to the fire scenario. In the AIEva model, considering the panic level of occupants caused by fire, \( \beta \) could be expressed as the function of danger eject factor (fire danger) of grids within the neighborhood.
\[\beta = f(q) = \begin{cases}
1.3 & \text{if } q < 0.5 \\
1.1 & \text{if } 0.5 \leq q < 0.8 \\
1.0 & \text{if } q \geq 0.8
\end{cases}
\]

(11)

Where, \( q = q_\text{fire eject factor} \times n^{-1} \sum q_{i,j} \), which means the mean value of fire danger eject factor of grids within the neighborhood, \( n \) is the grid number. If \( q_\text{fire} = 0 \), then \( q = 1 \).

Eqs. (9) and (10) indicate the person walking speed in common. In large public buildings, there exist some special evacuation zones like corridor and stairs inside. Within these zones, the movement of occupants may be assumed to be consistent with the stream speed of crowd since individual’s ability of self-motivation is restricted. Therefore, the walking speed of each occupant tends to be uniform in these areas. The self-motivation events like overpass hardly happen. Predtechenski and Milinskii formula [11] is adopted to determine the walking speed as the function of people density in the evacuation passage and corridor.

For horizontal paths:
\[u_k = m \cdot (112D^4 - 380D^3 + 434D^2 - 217D + 57)
\]

(12)

where, \( m = 1.49 - 0.36D \), here \( D = L/D_0 \), \( L \) is the average projection area of one person, here it is \( 0.113 \text{ m}^2 \).

For downstairs movement:
\[u_k = \alpha \cdot m \cdot (112D^4 - 380D^3 + 434D^2 - 217D + 57)
\]

(13)

where
\[
\alpha = 0.775 + 0.44 \exp(-0.39 \cdot D) \cdot \sin(5.06D - 0.224)
\]

(14)

The equations above are used to model the quantitative factors by mathematical method, such as walking speed and coordinate. Actually, there exist a lot of factors which are unable or hard to be described by determined mathematical formulas. Their effect could be determined by qualitative analysis only. Some researchers have studied and analyzed these factors through analyzing experimental data. Some rules are concluded by statistic method. For example, such rule like 'once the sight line is blocked by fumes, the walking speed of occupant has to slow down' illustrates the general behavior of
occupants under fire conditions. Therefore, AIEva considers these qualitative factors by rule reasoning mechanism.

The rule reasoning mechanism in AIEva system includes knowledge database, reasoning engine and blackboard. The forward reasoning, i.e. the data driving reasoning mode like ‘if – then’, is adopted as reasoning engine. Through the logical reasoning mechanism, based on the original information provided by agents, the system could simulate the effect and restriction of certain environmental condition on the evader’s behavior.

The interaction between occupants and fire field exists as long as the building is on fire. Representation of the interaction establishes the combination between the two models mentioned above: evacuation simulation model and fire simulation model. Actually, in the fire field, there are not only the fire hazards that may bring to occupants but also the behavior that occupants may perform against the fire field for balance of safety and efficiency. Therefore, the interaction for occupants can be divided into two categories: hazard and behavior response.

Under fire condition, fumes are the main factor that threatens occupants’ safety, which will be introduced as the case of rule reasoning mechanism in this paper. Due to the limit of roof, hot fumes layer will form on the top of the fired room. With the increase of fumes, the hot fumes layer becomes thick, and the temperature will increase. Through FDS simulation, various quantitative results (soot density, CO, CO2 etc.) at any point in the fire field can be calculated as a function of time. In the mean time, some experimental data has indicated the relationship between the duration occupants are exposed to certain volume of toxic substances and the corresponding hazard to human body. Referring to this, it is possible to estimate the potential toxic hazard of combustion products. Besides toxic gases, the heat release in fire field is another potential hazard to occupants. Thermal radiation from hydrocarbon fires may pose significant damage to personnel, causing severe burn injury. Normally blistering of skin is regarded to occur when the skin surface reaches a temperature about 55 °C [9]. Burn severity is divided into three levels. According to the conclusion of Mehta et al. (1973), burn severity depends on the energy absorbed after the skin temperature has reached 55 °C. FDS model is also capable of calculating temperature property at gas phase and solid obstructions. The quantity “Heat Release Rate” (HRR) can be obtained for awareness of the amount of energy absorbed in certain areas. From these data, the hazard assessment for thermal radiation can be made. Consequently the harm condition of fire could be determined with reference to certain data of people safety.

The critical condition of fire danger could be determined by the following cases:

1. When the fumes layer is higher than the characteristic height of man’s eyes, if the radiant intensity of the upper layer of smoke could harm people, it is taken as the dangerous state. Research data indicates that the harm will form at the fumes temperature of 180 °C, so the critical temperature of fumes layer radiation could equal the value.

2. When the fumes layer is lower than the characteristic height of man’s eyes, the harm to the people is caused by direct burn or...
inbreathing of heat gas. Here another lower critical temperature of fumes layer should be used to express the dangerous state. Based on experience, the value in the model is now determined to 115 °C.

(3) When the interface is lower than the characteristic height of man’s eyes, another method to judge whether the harm has formed is checking the critical concentration of the hazard burning product. For example, when concentration of CO reaches 2500 ppm, serious hazard to occupants will happen. The critical height of man’s eyes is normally 1.2–1.8 m, the model takes it as 1.6 m.

AIEva utilizes FDS to achieve calculation data with respect to fire field as the input variable and thus confirms hazard parameters of the grid within the neighborhood at each time step. Whichever critical condition is satisfied, it is thought as hazard happens. Injury and incapacitation are direct hazards that occupants may suffer in the fire field. Based on the hazard assessment above, the status of occupants will be changed according to health and mobility decrease, etc.). These changes will certainly influence occupant’s behavior in evacuation simulation model.

Additionally, smoke spread will result in the decrease of visibility in environment. Occupant behavior may turn inefficient when they move through smoke. Thus smoke density is a potential barrier for safe evacuation. Researchers proposed allowable smoke density and visibility that permits safe escape, as listed in Table 1 [12]. The influence of smoke density on velocity is considered by velocity correction coefficient γ. The influence of smoke density on visibility is considered by visibility that permits safe escape, as listed in Table 1 [12]. The visibility that permits safe escape, as listed in Table 1 [12].

The following rules are suggested to process the fire factors effect on movement speed at each time step:

(1) When the lower air layer within the target grid is higher than 1.8 m, the person will keep on moving to a certain exit at a probability of 90%. The movement speed is adjusted on the basis of uk, the speed correction coefficient γ equals 0.9.

(2) When the lower air layer within the target grid is lower than 1.5 m, and allowable smoke density and visibility are reached or exceeded, the person will select another exit at a probability of 40%. The movement speed shall decrease; the speed correction coefficient equals 0.9.

(3) When the lower air layer within the target grid is lower than 1.2 m, and allowable smoke density and visibility are reached or exceeded, the person will select another exit at a probability of 60%. The movement speed decreases further, the speed correction coefficient equals 0.6.

(4) When the fumes parameter of the target grid reaches critical condition (2) and (3) above, the person could be thought to have lost the ability to move, and taken as dead.

When the above rules are applied in the special area specified by AIEva, such as aisles, stairs, occupant’s movement is restricted by crowd and the flow speed is decided by the fumes layer height of the grid in front of the crowd. In the model, when the height of lower air layer is less than 1.5 m, the visibility of human’s eyes is very low, and panic psychology will enhance. The crowd will easily be disordered. The walking speed of flow is influenced further. Here flow speed could still be corrected by speed correction coefficient γ in the rules above.

Behavior response means the adjustments occupants may make to evacuation strategy in response to fire and smoke. The behavior response becomes sophisticated once the incident involves fire. Various actions may be taken since the inherent quality and physical environment of individuals are different. Broadly, the available strategic options can be categorized as “evacuation”, “reentry”, “fire fighting”, “moving through smoke”, and “turning back” [13]. These behaviors will be considered into the model as rule in the next version of AIEva.

AIEva system determines the location of every occupant according to the movement model above and calculates the walking speed of occupant. The speed vector Pu=(u1, u2, ..., uN) is used to describe speed information of all agents within the model space at time t. Then according to the initial location of each person, through iteration method, location of each person at any time could be solved out. The calculation equation is as below:

\[ L_{t+1} = L_t + U_t \Delta t \]  (15)

Through Eq. (15), we could actually describe the movement tracks of all occupants within the building. Therefore, the model could trace the movement process of each individual besides obtaining the final evacuation time.

3. Evacuation Simulation Program based on Agent

AIEva introduces the object oriented program (OOP) design method to realize the physical and mathematics model in computer mentioned above. The fumes level and fire scenario are simulated by FDS module. Coupled with the building deformation data derived from the structural analysis, the integrated process of evacuation is represented in a given fire scenario.
AIEva consists mainly of fire information database, core analysis module, rule reasoning mechanism and graphics platform etc. The system frame is shown as Fig. 2.

The fire information database is the core database to connect fire and structural analysis program. The simulation output data required by AIEva, such as fumes parameter, is stored. When obtaining these data, a data mapping tool is required to transfer the data from database to the spatial grids for storage through coordinate mapping. The data information will later become one member data of the grid object and the parameters of reasoning and computing for simulation.

The core analysis module, which is mainly responsible for computing and deciding the location of each agent at the next time step by environmental and other input information, is the key module of the entire system operation and the brain of the agent. The OOP method is adopted in the module and the entire evacuation process is abstracted as the environmental object and the Agent objects. The environmental object, which includes the spatial location information and all environmental factors of each grid under fire, represents the environment information like layout of building plane and the fire scenario at different times. Evaders in the fire are represented by the agent objects in AIEva system. According to various environment information, such as the layout of the building, the height of the fire fumes, and people density, each agent object makes decision and takes action through core analysis module, so as to determine the location at the next step. Each agent object moves in terms of time sequence, and the variety of fire scenario and environment, the entire dynamic evacuation process thus may be simulated. Fig. 3 shows the composing of the objects.

The numerical calculation module is programmed in terms of the equations in the mathematics model above with certain logic flow. It receives information and parameters transferred by agents, and the relevant mathematics equations are called for computing. Then judgment and analysis are processed to finally give out a speed for each agent. The result is transferred to intelligent decision-making module for processing. The module is mainly used to deal with the influence of some certain and quantitative factors on the movement speed. At last it outputs the revised velocity.

The reasoning mechanism based on the rules is adopted to deal with those uncertain factors that are hard to quantify but have rules in AIEva. Through knowledgeable abstract, rules are formed and stored in the rule database. The rule reasoning mechanism consists of knowledge base system (KBS) and reasoning machine. The KBS is the information storage and inquiry module for storing knowledge, rule and conclusion, including the synthetical database and rule database. Reasoning machine is the analysis module which calls the logical rule to give the decision according to the input information. Currently, the rules in the inference engine are not abundant yet. It is to be improved in future study.

An integrative intelligent decision-making module has been created to deal with the conflicts between the numerical calculation and rule reasoning module and harmonize the correlation between one agent and another, and between an agent and a building.

Additionally, in order to achieve 3D dynamics effects for evacuation simulation, a visualization program named as 3D Render has been developed on the OpenGL platform. OpenGL, consisting of over 250 different function calls, has been widely used in CAD, Virtual Reality and other fields [14]. As a post-processor of AIEva, 3D Render can provide scenarios from any angle of view. Obviously, the representation in this virtual reality environment is more animated than in 2D view.

The graphic platform of AIEva could be chosen freely. The system adopts the simple graphic performance module developed by Visual C++. The evacuation process could be shown more truly in the future with the assistance of advanced graphic platform. Meanwhile, with the help of the analysis function in the advanced platform, more detailed research work for evacuation process shall be performed.

According to the physics model and mathematics model above, the system flow can be shown as Fig. 4.

Agent is the basic element of the whole simulation model, which represents the occupants’ behaviors in the evacuation progress. In fact, it is the combination of individual occupant and the ambient

Fig. 8. Layout demo of evacuation status. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
'neighborhood' environment. During simulation process, agent receives information from its surrounding environment and other agents and the information is sent to the intelligent decision-making module as 'brain' for analysis. Based on the resulting data, the action at the next step is decided. Fig. 5 presents the structure of a single agent and its function relationship in the model.

4. Case Study

One of the gymnasiums as the competition venues of 2008 Beijing Olympic Games has been taken into study as a case of the AIEva system. The studied building is a steel grid structure with a large span that covers an area of 33×33 m with an overall height of 11 m from the ground to the top. The fire scenario is designed as: during a scientific exhibition held in the gym, due to carelessness, the northwest platform is burned and fire occurs. According to the building layout of the gym and the amount of the burning material, the fire load is designed as 8 MW. The fire development curve is specified as medium velocity t, and the ventilation and active fire control devices are taken into account while the influences of special weather conditions are not considered. The fire scenario described above is simulated in FDS environment, as shown in Fig. 6. Afterwards, the structural response under fire conditions is analyzed. The analysis process and result is shown as Fig. 7. Then, the results of fire simulation and structural analysis have been stored to the core database automatically by the AIEva system.

Occupants are generated randomly before evacuation starts. The initial location and inherent qualities like gender are randomly given to each individual. Then some evacuation properties relevant to qualities are assigned accordingly. The health and mobility status is assumed to be normal when occupants are generated. The size of the space grid each occupant takes up is regarded as 400 mm×400 mm. When fire occurs at the northwest of the gym, only the south exit opens. Evacuation begins when fire alarm detects the smoke, i.e. when gas volume fraction somewhere in the field exceeds 2%. Reaction time is assumed as 10 s for the occupants near fire source, 20 s for others.

Fig. 8 shows some pictures of the evacuation process. The figure represents the evacuation state at different times after the fire occurred. The red area in the figure means the fumes concentration and the fumes layer height in the area have reached the level to threaten human life. The green area means where the structure has failed, which will influence the routes of occupants and firemen. The fumes level and data of structural failure were obtained from the system core database after fire simulation and structural analysis. It could be seen from the simulation process that the speed changed as the result of obstacle avoidance in the evacuation routine and influence of persons around. In the process of evacuation, due to the limit of exit, congestion happened. The speed of the people backward was restricted. One will either wait in the current grid, or move around, or try to search for free space. Therefore, the amount and width of exit produce important effect on the evacuation character. The evacuation time can be read from the interface, and eventually the total time of evacuation is 479 s.

5. Conclusion

With the increase of processor power and memory capacity of modern computers, it becomes more and more popular and effective to conduct simulation experiments on computer. In this study, an evacuation simulation model named as AIEva, based on the agent evacuation dynamic mathematical model, is proposed, which aims at simulating occupant evacuation in fire environments for large public buildings through agent simulation technique and other artificial intelligence methods. It will be useful for identifying fire safety and evaluating evacuation efficiency for architectural plans.

In addition, an evacuation simulation program is developed for AIEva based on fine networks (Fig. 9). The integration of evacuation simulation model and fire simulation model is crucially important. Toxic and physical hazard assessment quantifies the harm that fire acts on occupants, which will change the values of occupant status. Accordingly different behavior rules may be adopted. In addition, the evacuation strategy will be adjusted in terms of external circumstances. Therefore, this behavior trigger system reflects both environmental factors and human body conditions.

A simulation experiment is conducted. One of the selected gymnasiums for the competition venues of 2008 Beijing Olympic Games has been taken into study as a case to simulate the evacuation and fire fatalness of the stadium with the computer simulation program. The process of fire growth and smoke spread can be observed through simulation. Fire and smoke influence on occupants increases the clearing time significantly. It can be seen from the results of the simulation that the system can reflect the character of group, congestion and dense flow during the evacuation of large public buildings. Otherwise, the results indicate that occupant behavior under emergency conditions is quite complicated due to a large number of factors which are involved. Actually, these factors include not only environmental elements such as fire and fumes, but also some inherent human qualities. Some of these factors are not even fully understood by researchers at present, which make some factors and the relationships between them difficult to quantify. Furthermore, fire safety evacuation models are difficult to verify since results of the
incident are stochastic and it is impossible to conduct repeatable experiments. These disadvantages hinder the development of computer simulation models. But with further development of technology and method of evacuation study, more complex psychological aspects of escape movement will be considered and more accurate model could be developed. Further work is being carried out to attempt to improve the flexibility and validity of this programme. Satisfying results must be achieved by the computer simulation.

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